2016-1

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Rajeev Ravindran
Technological University Dublin

Amit Jaiswal
Technological University Dublin, amit.jaiswal@tudublin.ie

Recommended Citation

Ravindran, R. & Jaiswal, A. K. (2016). Exploitation of food industry waste for high value products. Trends in Biotechnology, 34(1), 58-69. doi:10.1016/j.tibtech.2015.10.008

Trends in Biotechnology
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Review

Exploitation of Food Industry Waste for High-Value Products

Rajeev Ravindran[1] and Amit K. Jaiswal[1,*]

A growing global population leads to an increasing demand for food production and the processing industry associated with it and consequently the generation of large amounts of food waste. This problem is intensified due to slow progress in the development of effective waste management strategies and measures for the proper treatment and disposal of waste. Food waste is a reservoir of complex carbohydrates, proteins, lipids, and nutraceuticals and can form the raw materials for commercially important metabolites. The current legislation on food waste treatment prioritises the prevention of waste generation and least emphasises disposal. Recent valorisation studies for food supply chain waste opens avenues to the production of biofuels, enzymes, bioactive compounds, biodegradable plastics, and nanoparticles among many other molecules.

Food Waste as a Global Concern

The global population is expanding at an exponential rate every year. There is a huge demand for food and energy to meet the needs of society. Rapid urbanisation combined with slow progress in the development of and ineffective waste management strategies leads to the accumulation of food waste. A study published by the EU in 2010 revealed that almost 90 million tonnes of food waste are expelled from the food manufacturing industry every year [1]. Food waste, being high in nutritional content, putrefies on accumulation, providing breeding grounds for disease-causing organisms. This poses serious environmental issues and very few options exist today to deal with them. While preventive measures can be taken to reduce the generation of food waste it is important to deal with the existing accumulated food waste. The idea of converting food waste into energy and other chemicals used in our daily activities is an area of research with huge potential and opportunities. This review deals with the types of food waste and problems associated with them, the legislation pertaining to reducing food waste as well as using it as a renewable **feedstock** (see Glossary), and the various products and the latest valorisation techniques developed in recent years using food waste as a raw material.

Food Industry Waste as a Renewable Resource

Food industry waste is particularly interesting for renewable energy researchers as it is mostly lignocellulosic in nature, with high cellulose and lignin content (except animal-derived food waste). Many studies have reported on various technologies for the conversion of food waste such as apple pomace and brewers' spent grain into biofuel [2,3]. Cellulose and hemicelluloses on enzymatic breakdown release glucose and xylose, which can be converted into ethanol by fermentative microorganisms [4]. Furthermore, lignin on pyrolysis and anaerobic digestion yields H_2 and CH_4 [5]. In the quest for renewable energy resources with the backdrop of rising oil prices, one overlooks the fact that food waste is a reservoir of other value-added chemicals. Recent studies suggest that the production of bulk chemicals from biomass waste is 3.5 times more profitable than converting it into biofuel [6]. Meanwhile, **biorefinery** is an emerging

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Food supply chain waste is an abundant resource with significant potential to be used as raw material for fuel production and other industrially viable compounds.

The latest legislation on waste management places much emphasis on the valorisation of food industry waste and the technologies associated with it.

Biorefinery is a novel concept analogous to the petroleum refinery where all components of the raw material are converted into commercially important products (e.g., biofuel, enzymes, oils, nutraceuticals).

This review discusses the latest developments in the use of food supply chain waste with emphasis on the most innovative products developed from such waste.

[1]School of Food Science and Environmental Health, College of Sciences and Health, Dublin Institute of Technology, Cathal Brugha Street, Dublin 1, Republic of Ireland

*Correspondence: amit.jaiswal@dit.ie, akjaiswal@outlook.com (A.K. Jaiswal).

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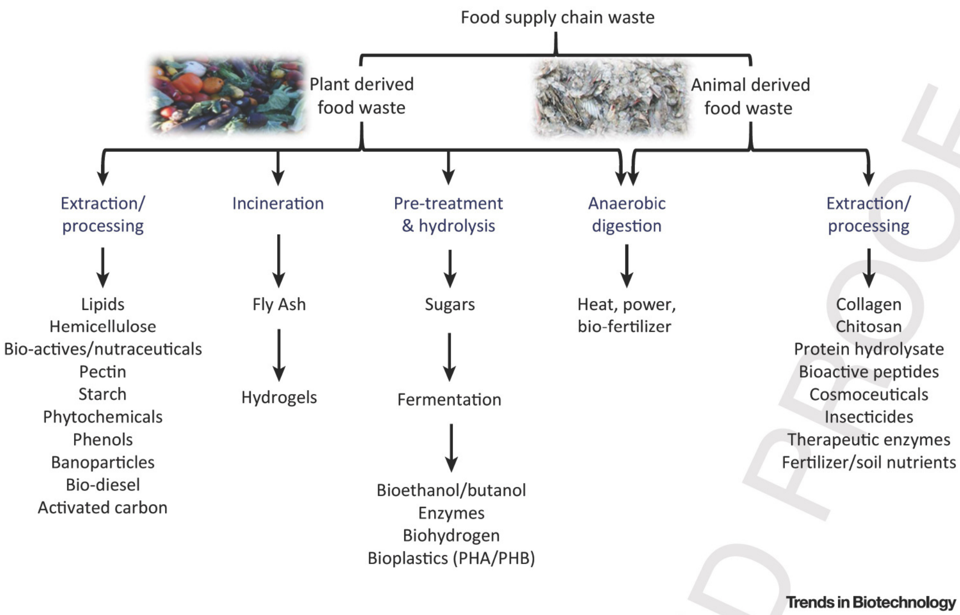

Figure 1. Possible Commercial Products That Can Be Derived From Food Supply Chain Waste.

concept in the field of biomass waste management suggesting that all kinds of biomass-derived material can be converted into different types of biofuels and chemicals through various conversion processes [7]. Figure 1 provides a comprehensive overview of the various functionalised molecules that can be derived from food supply chain waste (Box 1).

Various food industry processes (processing, packaging, transportation, and storage) in their current form are highly inefficient considering the volume of waste they generates during their various stages. These wastes are mainly organic in nature and characterised by high **biological oxygen demand (BOD)** and **chemical oxygen demand (COD)** and variations in composition and pH owing to seasonal variations and handling processes. Such wastes lead to bacterial contamination due to the high water content and high accumulation rates, not to mention disposal management problems and the cost associated with them [8]. The present logistic strategies practised in the food industry are incapable of dealing with the hurdles of waste management. Incorporating technologies to derive value-added products, chemicals, and fuels is a positive step towards dealing with this problem. However, a steady and incoming flow of raw materials is crucial to keep the industry interested in valorisation studies of food waste. Post-consumer leftover food is the most obvious indicator of the available food waste raw material since is visible on a daily basis. However, waste generated from the last link of the food chain raises several problems since it is a mixture of materials that are heterogeneous in nature and not segregated. By contrast, waste from each stage of the production process is consistent in its chemical composition. Therefore, variations in feedstock can be overcome by novel collection and storage strategies, making it easier for valorisation. There are no exact reports on the amount of waste generated from different food processing industries. Table 1 provides an estimate of the various forms of food waste generated in Europe and the USA.

Current Legislation on Waste Management

Legislation pertaining to waste management in Europe started in the 1970s with the European Economic Community, the precursor to the EU, trying to define ‘waste’ as a basis to devise laws and regulations with respect to the production, handling, storage, transport, and disposal of waste by minimising the ill-effects related to waste generation on health and the environment [9].

Glossary

Biological oxygen demand (BOD): refers to the amount of dissolved oxygen required by microorganisms to assimilate the organic matter present in a water sample at a specific temperature over a certain period of time.

Biorefinery: sustainable processing of biomass into a wide range of marketable products, including fuels. Initially, the complex polymers that constitute biomass can be broken down into their component building blocks (carbohydrates, proteins, fatty acids) and subsequently converted into value-added products.

Chemical oxygen demand (COD): a test commonly employed to measure the organic compound content in water. It is usually performed to determine the amount of organic pollutants in surface water or waste water, an indirect measure of water purity.

Composting: a biological process where microorganisms grow on waste material in a controlled manner, breaking down the organic fraction; the end product, called compost, is rich in soil nutrients and can be used as fertiliser.

Feedstock: any form of renewable biological material that can directly or indirectly be converted into fuel or other compounds. Biomass feedstock includes plant and algal biomass, which can be converted into fuel sources such as combustible alcohols or commercially important products such as enzymes.

Box 1. Food Supply Chain Waste

There are various stages in the food supply chain where waste is typically generated. These stages are: post-production, handling and storage, manufacturing, wholesale and retail, and consumption. Spillage, spoilage and storage loss or out-grading, pest infestation, and loss of quality during storage can be the main reasons for loss of agricultural produce after harvesting. In the manufacture of products, waste is generated during processing stages such peeling, washing, boiling, and slicing and by process losses, byproducts such as pomace and spent grain, and wastes from plant shutdowns or washing. In wholesale/retail, waste accumulates due to damage and expiry of products or surplus. Consumer waste is the most evident, with waste accumulated due to leftovers, storage waste, and spoiled food.

The sources of food processing plant waste can be classified into four categories: agricultural waste, food processing waste, distribution waste, and consumption waste. High sanitary risk is characteristic of fish and meat processing residue and therefore this is an unlikely candidate for valorisation. However, researchers have devised methods to covert fish waste into protein hydrolysate and amino acids such as Tyr, Met, His, and Lys, which has antioxidant properties [63]. Nonetheless, much of the efforts in waste processing have been focused on plant waste.

According to their biochemical characteristics, food supply chain waste can broadly be classified as plant-derived waste or animal-derived waste.

Plant-derived food waste arises from cultivated grains, fruits, and vegetables. Paddy, wheat, and corn residues are the major sources of agricultural waste that are extensively used for the production of biofuels. Rice is the staple food of people in living in the East. The amount of rice straw available for feedstock accounts for more than 730 million tonnes/year distributed among Africa, Asia, Europe, and America. This can amount to almost 205 billion litres of bioethanol annually [64]. Rice straw has a high cellulose and hemicellulose content and can readily be converted into bioethanol on enzymatic hydrolysis [65]. Wheat processing leads to four products that were once considered waste: straw, husk, chaff, and bran. Many studies have concluded that wheat husk is an ideal candidate for biofuel production [66]. The extent of wheat production waste can be observed from the fact that, in 2009, global wheat production amounted to 682 tonnes, with the EU alone contributing 150 million tonnes. Rye is also an important grain, used to make bread, beer, whisky, vodka, and animal feed. Almost 20% of rye is not edible and is thus treated as agrowaste [67].

The meat, fish, and poultry industries are the largest source of animal food industry waste [68]. Animal-derived food waste contains rather high amounts of protein and cannot be discharged into the environment without proper treatment. The major sources of animal waste include slaughter houses derivatives that cannot be sold, such as organs and other visceral mass [69]. The use of fish, shrimp and other seafood for the production of value-added products is mentioned above. Another source of animal-derived food waste is the dairy industry. Cheese whey is a major waste product of the dairy industry and has been a popular raw material for the production of protein extracts and saccharides. It is produced in massive amounts during cheese manufacturing and has a mass per product mass ratio of 4.0–11.3 (specific waste index) [70].

Table 1. Food Supply Chain Waste Estimates with Respect to Geographical Location

Food Supply Chain Waste Examples	Volume Available (tonnes/year)	Region	Refs
Olive pomace	2 881 500	Worldwide	[30]
Waste vegetable oil	50 000–100 000	UK	[71]
Tomato pomace	4 000 000	Europe	[8]
Wheat straw	57 000	USA	[72]
Brewer' spent grain	30 000	Worldwide	[73]
Potato peel	70–140	Worldwide	[74]
Sugarcane bagasse	0.600	Brazil	[75]
Grape pomace	700	France	[76]
Apple pomace	3 000 000–4 200 000	Worldwide	[77]
Rice husk	120 000	Worldwide	[78]
Orange peel	700	USA	[79]
Cereal waste	40 000–45 000	Europe	[80]

In the legal sense, food waste is treated in the same way as normal waste that is nonhazardous if and only if it does not exhibit any properties that may render it 'hazardous'. This is with the exception of animal byproduct waste. Stringent controls are applied to its transport, handling and storage, treatment, and disposal through Regulation (EC) No 1069/2009. However, animal byproduct waste that is meant for incineration, **composting**, or plant or biogas production does not come under this regulation [10].

The New Waste Framework Directive (WFD)

Directive 2008/98/EC was adopted to introduce a new approach to the handling of waste and its management. Accordingly, the WFD and hierarchy prioritises the prevention of waste generation, followed by processing for reuse and recycling, with disposal as the least favoured stage of waste management [11] (Figure 2). Food waste was considered a special case in the WFD, focusing on three key points: the separate collection of biowaste, treatment of biowaste to ensure maximum environmental protection (composting and digestate), and the development of techniques to produce environmentally safe materials from biowaste. The new directive requires member states to implement national waste prevention programmes. These programmes undergo evaluation every 6 years and should be revised appropriately. They can function as independent programmes or can be incorporated into waste management plans or other environmental policy programmes. If incorporated into a waste management plan or any other programme, the waste prevention measures should be clearly identified. Article 29(3) requires member states to determine specific qualitative and quantitative benchmarks for the waste prevention programmes adopted so that their progress can be monitored and measured. Meanwhile, Article 29(5) assists the Commission in creating a system where the best practises for waste prevention can be shared based on which guidelines can be formulated to help member states [12].

In 2010, further communication from Commission on the future steps for biowaste management concluded that composting and anaerobic digestion of food waste are the most promising measures. A commercial anaerobic digester can create, heat, power, and biofertiliser from food and farm waste. Commercial anaerobic digesters have left their infancy over the past few years. A report published in March 2013 counted 106 anaerobic digesters in the UK alone, with a processing capacity of 5.1 million food waste and farm waste annually [13]. Municipal waste,

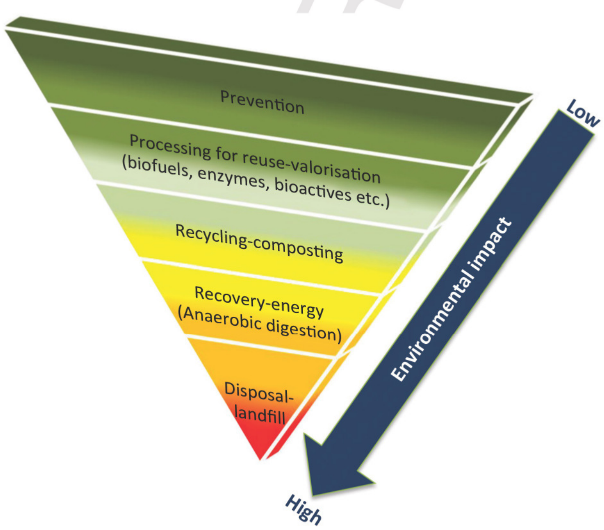

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Figure 2. Hierarchy for Waste Processing. Adapted, with permission, from [71].

especially kitchen, canteen, and garden waste, are utilised in the composting process. The Commission considers that digestate and compost that meet 'end of waste' criteria have undergone recycling [14].

Regulation (EC) No 1907/2006 of the European Parliament and Council lists rules and regulations for the production and marketing of newly produced chemicals within the EU. The Regulation Evaluation Authorisation and Restriction of Chemicals Legislation (REACH) requires the manufacturer to obtain a registration for the chemical concerned if its production equals or exceeds 1 tonne per annum. This may pose a barrier for the production of new chemicals, although sharing the cost of procuring hazard and risk assessment data by the importer and the producer can be considered. Small-scale producers that focus on the production of novel compounds and mixtures via food waste reprocessing will find compliance issues a major hurdle for the commercialisation of the process in accordance with the REACH legislation [15].

Bioeconomy

There is no explicit mention or definition of the valorisation of food supply chain waste in the WFD. However, the objective of using waste for value-added production is comes within the spirit of the directive. 'Bioeconomy' is a new concept coined by the European Commission in 2012 to address the possibilities of the conversion of renewable biological resources into economically viable products and bioenergy. Although not a new piece of legislation, bioeconomy emphasises streamlining existing policy in this sector. It is based on three main pillars: (i) investments in research, innovation, and skills; (ii) reinforced policy interaction and stakeholder agreement; and (iii) enhancement of markets and competitiveness. Through bioeconomy, the European Commission aims to answer issues such as increasing global demand for food, natural resource depletion, and the impact of environmental pressures and climate change [16].

Recent Valorisation Studies on Food Industry Waste

The value of the substrate is determined by the biomass conversion process. The operational cost and the value of the target products are the two main factors that determine whether a biomass conversion process is feasible. It is therefore necessary to evaluate the current trends and recent development of technology in the conversion of food supply chain waste. A large spectrum of commercially important products such as biofuels, enzymes, organic acids, biopolymers, nutraceuticals, and dietary fibres have been developed from the bioconversion of food industry waste [17]. This section provides the latest developments in the valorisation of food industry wastes into value-added products.

Biofuels

Plant biomass has been used for the production of fuel ethanol for almost a century. The basic idea behind bioethanol production is that enzymatic hydrolysis of lignocellulose releases fermentable sugars that can be converted into ethanol. The term 'biofuel' encompasses a wide variety of products such as bioethanol, biodiesel, biohydrogen, biobutanol, bioether, biogas, and syngas [18]. Pretreatment is a necessary step in bioethanol production since recalcitrant substances in lignocellulose will hinder efficient enzymatic hydrolysis [19]. In recent developments, bioethanol was produced from food waste using carbohydrases and *Saccharomyces cerevisiae* as the fermentative microorganism. The two modes of fermentation – viz. separate hydrolysis and fermentation (SHF) and simultaneous hydrolysis and fermentation (SSF) [20] – were able to obtain ethanol yields of 0.43 g/g and 0.31 g/g, respectively. The prospect of using instant noodle waste as a substrate for ethanol production was probed by Yang *et al.* [21]. Oil removal pretreatment was necessary for this purpose. Glucoamylase and α-amylase were used for enzymatic hydrolysis of the substrate. Employing *S. cerevisiae* under the SSF mode, a 96.8% conversion rate was obtained with a maximum ethanol yield of 61.1 g/l.

Biodiesel is a value-added product of cooking oil waste. Soy bean oil, canola oil, and cooking oil waste have been successfully converted into biodiesel by various methods. Lipolytic enzymes such as Lipozyme TL IM and Novozym 435 are employed in the transesterification process to convert cooking oil into biodiesel [22,23]. In a recent study, carbohydrate-derived solid acid catalyst was used for the production of biodiesel from low-cost feedstocks such as palm fatty acid distillate, which is a byproduct of the palm oil industry [24]. Besides commercial lipases, microbial enzymes have also been used for biodiesel production. Mixed lipases from *Candida rugosa* and *Rhizopus oryzea* were immobilised on a silica-gel matrix by Lee *et al.* [23] for the production of biodiesel from soy bean oil. High conversion rates were achieved during this study and the immobilised mixed lipases were reused for 30 cycles. Biohydrogen has been produced using oil palm fruit bunch, sweet sorghum, and wheat straw in separate studies. In all three studies, dark fermentation was used as the mode of hydrogen production. Genetic enhancement of the fermentative organism resulted in better yields [25–27]. *Enterobacter*, *Bacillus*, and *Clostridium* are the most popular microorganisms used for biohydrogen production [28].

Industrial Enzymes

As in bioethanol production, lignocellulose pretreatment followed by enzymatic hydrolysis is the essential step for enzyme production from food waste. In some cases the enzymatic hydrolysis stage can be omitted for certain fungal organisms that naturally grow on plant biomass. Examples of such organisms include *Scytalidium thermophilum*, *Melanocarpus* sp., *Aspergillus* sp., and *Pleurotus* sp. [29]. Food waste has been favoured as an ideal candidate for enzyme production and therefore several food supply chain wastes have been used for the production of commercially important enzymes. Oxidative enzymes such as cellulase, laccase, amylase, xylanase, phytase, and lipase have been the focus of production using organic food waste residues [30–34]. The motive behind the utilisation of food waste for enzyme production is the associated cost. Commercial enzyme production is a cost-intensive process, with almost 28% of the operational cost dedicated to raw material procurement [35]. In lieu of solving this problem, several studies have focused on the utilisation of lignocellulosic food waste as a raw material for enzyme production. As mentioned above, microbial strains are capable of degrading the complex polymers in plant biomass and utilise the sugars released for their sustenance. This fact is taken advantage of when using food processing industry waste as a raw material for enzyme production. Additionally, high enzyme activity can be achieved by using media optimisation techniques and genetically superior enzyme-producing microbes. The solid state fermentation mode is preferred over submerged fermentation mainly due to the operational cost. According to Singhania *et al.* [36], the operational cost of solid state fermentation is one-tenth of that of submerged fermentation. Also, solid state fermentation replicates the natural environment for enzyme production in a bioreactor, which has been proved to increase enzyme yield [37].

Food waste is naturally heterogeneous in nature and therefore can cause problems in downstream processing. This can result in increased costs for enzyme isolation and purification. One-step purification and immobilisation of enzymes is a recent innovation in enzyme recovery [38]. Enzyme immobilisation and purification via one step can be achieved by following three different strategies: immobilisation via one point, employing custom-made supports that are specific to the target protein based on certain structural features, and the application of site-directed mutagenesis in an effort to introduce specific domains into the target protein molecule that show affinity to the heterofunctional supports [39–41].

Bioactive/Nutraceuticals

A detailed analysis of studies on the conversion of plant-derived food waste reveals that the extraction of value-added chemicals such as antioxidants and dietary fibres is becoming as popular as liquid fuel and biogas production (Table 2). Rice bran is a byproduct of the rice milling industry. It is rich in fibre, proteins, minerals, and vitamins, and phytochemicals such as

Table 2. Food Waste Origin and Target Molecules for Recovery

Waste Origin	Source	Target Product	Refs
Cereals	Rice bran	Insoluble dietary fibre	[81]
	Sesame husk	Insoluble dietary fibre	[81]
	Wheat bran	Fructans	[82]
	Oat milling waste	Antioxidants	[83]
	Brewers' spent grain	Ferulic acid	[84]
Oil crops	Olive oil mill waste	Pectin and phenol	[85]
	Winter oil seed rape	Phytosterol	[86]
	Kalahari melon seeds	Phytosterol	[87]
	Soy whey waste water	Isoflavone aglycone	[88]
Fruits and vegetables	Orange peel	Apocarotenoid	[89]
		Limonene	[90]
	Apricot kernel	Protein isolate	[91]
	Apple pomace	Polyphenols	[92]
	Tomato pomace	Lycopene	[93]
	Tomato skin	Carotenoids	[94]
Meat	Chicken byproducts	Proteins	[95]
	Slaughterhouse byproducts	Collagen	[69]
Fish and seafood	Fish leftovers	Fish protein hydrolysate	[96]
	Shrimp and crab shells	Chitin, carotenoid pigments	[97]
Dairy	Cheese whey	Lactoalbumin	[98]

tocopherols and polyphenols. The consumption of rice bran has been reported to have antitumour effects and cardiovascular health benefits and can lower cholesterol. Irakli *et al.* [42] found that addition of rice bran to wheat flour by 30% increased the antioxidant activity of bread fivefold. Although the vitamin E content was reduced, the phenolic content increased and the bread produced was overall acceptable. Citrus peels and fruit pomace residues are good sources of phenols and carotenoids [43,44]. These chemicals can be used for enhancing the shelf life of food and beverages by preventing off-flavour formation. Pectin is a major component of all plant matter. It is used as a gelling agent in confectionery and a fat replacement in meat and meat products. Water-insoluble fibres are a food additive in functional foods that are used to improve intestinal health. Protein hydrolysates from seaweed have been used to impart seafood flavours in soups [45].

Nanoparticles

The development of nanomaterials from food processing residue is a fairly new area of research. In recent studies rice bran and wheat husk have been used as potential components to produce nanoparticles. Biopolymers such as xylan, cellulose, starch, and chitosan have been widely used to synthesise stable nanoparticles owing to being renewable resources [46]. The presence of silica in rice husk makes it an excellent material for nanoparticle production. Several methods have been invented to utilise rice husk for nanoparticle synthesis. Silica extracted from rice husk was used for *in situ* anchorage of Pt and Ni nanoparticles. Rice husk silica (RHS) texture was using a cationic surfactant (CTAB) and a nonionic surfactant (Span 40). The Span 40 RHS immobilised Ni particles onto its surface and exhibited high dehydrogenation activity and stabilised performance for the production of acetaldehyde [47]. In another study silver nanoparticles were synthesised using xylan obtained from wheat bran as the reducing and stabilising agent. A mild pretreatment was necessary to extract xylan from wheat bran. Silver nanoparticles were prepared by dissolving xylan in sodium hydroxide and then adding 1 ml of silver nitrate into the solution. After stirring for 5 min, the solution was heated to 100 °C for 30 min. The emergence of brown colour indicated the formation of silver nanoparticles [48].

Nanoparticles exhibiting antibacterial activity were developed using a cost-effective approach by Cui *et al.* [49]. They synthesised porous carbon from rice husk by carbonising it at 400 °C in a nitrogen environment for 2 h. The antibacterial activity of the newly prepared nanoparticles was as low as 25 μg/ml, inhibiting microbial growth. In another study nanosilica particles prepared from rice husk at a yield of 81% by a hydrothermal technique were found to be effective in the removal of organic dyes [50].

Biodegradable Plastics

Polyhydroxyalkanoates (PHAs) are plastic-like materials that are perfect replacements for petroleum-derived plastics. Similar to enzyme production, the main barrier in the commercialisation of PHAs is the high operational cost incurred during their production [51]. Therefore, lignocellulosic materials, preferably food waste and agricultural residue (due to their abundance and zero value), have been used as substrates for the production of PHAs and poly-3-hydroxybutyrate (PHB). Table 3 shows a cumulative list of microorganisms that have reported to synthesise PHA/PHB using various food industry wastes. *Burkholderia sacchari* DSM 17165 is a strain that is capable of metabolising glucose, xylose, arabinose, and other reducing sugars to produce PHB. In a study, the efficacy of wheat straw hydrolysate as a raw material for PHB production was tested. Shake-flask-level experiments showed that *B. sacchari* cells accumulated 60% g PHB/g cell dry weight with a yield of 0.19 g/g when wheat straw hydrolysate was used as the sole carbon source [52]. Venkata *et al.* [53] conducted an optimisation study on PHA production using mixed aerobic and anaerobic cultures and found that the microenvironment had the greatest influence on PHA production.

Spent coffee waste is an excellent substrate for PHB production. SCW contains 10% oil, which can be converted to PHB by *Cupriavidus necator*. After oil extraction, the residual solid is rich in cellulose and hemicellulose content. These solids were subjected to pretreatment followed by enzymatic hydrolysis in which the hydrolysate was used a carbon source for PHA production using *Burkholderia cepacia*. The microbe preferred hexoses over pentoses (mainly mannose and galactose), which were the predominating sugars in the hydrolysate. Moreover, the presence of levulinic acid acted as a precursor for 3-hydroxyvalerate resulting in the accumulation of P(3HBco-3HV) copolymer [54,55].

Table 3. List of Microorganisms used for PHA Production

Production Strain	Food Waste Sample	PHA Type	Refs
Bacillus firmus	Rice straw hydrolysate	PHB	[99]
Ralstonia eutropha	Bagasse	PHB	[100]
Halomonas boliviensis	Wheat bran + potato waste	PHB	[101]
Azotobacter beijerinickii	Coir pith	PHB	[102]
Burkholderia sacchari	Wheat straw hydrolysate	PHB	[52]
Mixed culture from activated sludge	Olive pomace	PHA	[103]
Bacillus megaterium	Oil palm empty fruit bunch	PHB	[104]
Saccharophagus degradans	Waste from tequila bagasse	PHA	[105]
Pseudomonas sp.	Grass	Medium-chain PHA	[106]

Chitosan

Chitosan is a derivative of chitin, the second most abundant polymer after cellulose. It possesses intrinsic properties such as antimicrobial activity, biodegradability, and biocompatibility [56]. These features of chitosan make it a widely sought candidate for the food, pharmaceutical, chemical, and textile industries. Its high cationic density and long polymer chains make it an effective coagulant/flocculent and it is used in water treatment facilities [57]. Shrimp shells are commercially used as a raw material for the production of chitosan. The process involves the use of strong acids and alkalis to remove the proteins and minerals from the shells. However, this may also lead to depolymerisation of the chitosan. Recently, researchers have started focusing on the use of proteases for the extraction of chitosan from shrimp waste from the fish industry. With the help of fish proteases a group of scientists were able to extract and depolymerise chitin from shrimp waste. By maintaining a high enzyme/substrate ratio (10 U/mg) they were able to achieve 80% protein removal and complete deproteinisation was achieved in 6 h. The chitosan obtained was successfully employed for unhairing effluents from the tanning industry [58].

Collagen

Collagen is one of the most common types of protein in multicellular organisms. It is fibrous in nature and provides structural rigidity in connective tissues as well as internal organs. Collagen, and its denatured form gelatin, are widely used in the cosmetic, pharmaceutical, and leather industries and also for medical applications. Animal food waste such as fish waste are widely used as raw materials for the production of collagen [59]. In a study, acid-soluble collagen was extracted from cod bone using 0.1 N NaOH to remove all noncollagenous protein [60]. Broiler chicken processing waste was experimented with as a raw material for the production of collagen casings by Munasinghe *et al.* [61]. Using acetic acid and pepsin they were able to extract collagen by centrifugation and subsequent lyophilisation. One of the most popular uses of collagen is in the food industry, where it is used to produce edible casings for meat products and sausages. However, managing the waste derived from biologically resistant collagen casings is becoming a serious problem. While landfill remains the current viable option for its disposal, a technoeconomic analysis has revealed that composting of charred casings was more appropriate with respect to agrochemical and financial aspects [62].

Outstanding Questions

How can waste valorisation strategies be incorporated into the various stages of food processing and logistics?

What are the technical hurdles associated with food industry waste considering its vast diversity?

Will the utilization of waste products as raw material for the synthesis of value-added products be an economically feasible idea?

Has the biorefinery concept been truly effective for all forms of food supply chain waste?

Concluding Remarks and Future Perspectives

The implementation of strict legislation for human health and environmental safety and the emergence of novel techniques for the recovery of commercially important biomolecules has caused enormous interest in food supply chain waste valorisation. The generation of food waste is inevitable, especially during the preconsumption stage. However, environmental damage caused by the formation of greenhouse gases and ground water contamination via food waste decomposition due to landfill can be largely avoided. Studies cited in this review have shown that food waste is a renewable resource for industrially important chemicals and can be used as a raw material for biofuel and enzyme production. Technologies that least affect the environment negatively (intelligent separation techniques), biochemical processing strategies (such as fermentation), and extraction processes for biologically active molecules raise economically interesting prospects for food waste. Technologies for the recovery of high-added-value compounds are pivotal to the utilisation of food waste for commercial applications.

Acknowledgment

The authors acknowledge funding from the Dublin Institute of Technology (DIT), Dublin, Republic of Ireland under the Fiosraigh Scholarship Programme, 2014.

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